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PRELIMINARY REPORT ON AUTOMATIC LEM MISSION STUDY

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ENG. 345

GRUMMAN AIRCRAFT ENGINEERING CORPORATION

PRELIMINARY REPORT ON AUTOMATIC LEM MISSION STUDY

LIST OF ILLUSTRATIONS

[redacted]

PREFACE

In mid-February 1963 a study of an automatic LEM mission was undertaken in accordance with the requirements of Item C-3 of LEM Engineering Memo L250-M03-2 by C. W. Rathke entitled "Technical Priority Efforts, Prime Responsibility For". From the onset, it was assumed that a LEM vehicle designed for automatic performance of the lunar landing mission would serve as an "unmanned"* trial vehicle prior to the manned landing attempt.

Under this assumption, work had progressed until early April 1963. At this time work was redirected so that the automatic mission became a possible alternate mode of the basic manned landing mission. The important factor in the redirection was that the crew would man the LEM and be capable of performing manual monitoring, switching, override and equipment alignment functions as required.

For example, the crew could perform:

Manual IMU alignment

Manual acquisition of CSM

Manual insertion of initial conditions into the computer

Manual monitoring of guidance and control equipment

Under the new ground rules, automation would be incorporated if the weight and schedule penalties were not severe, compared to the advantages obtained. In addition, for purposes of meeting an immediate objective of a report submission, only the descent flight to touchdown would be considered in the redirected study. It was

* No LEM crew inputs

also agreed that the work completed before redirection would be summarized and presented in a separate report; (work completed on the redirected study would be submitted at a later time). This report is a summary of the work completed before redirection.

I. INTRODUCTION

This report is intended to satisfy in part the requirements for a preliminary report on the Automatic LEM study. The basis for this study was determined in an agreement between Grumman (C. W. Rathke) and NASA (C. W. Mathews). It is confirmed in Grumman Memo LEM-IOM-62-47H dated 18 December 1962, page 4, item 3 under "Mission Plan and Test Programs". Its purpose is to study the performance and hardware implications of an entirely automatic LEM mission.

In order to determine the direction of this study, several ground rules were postulated and work has progressed based on these.

At the writing of this report, much of the LEM system was in the state of early development so that the information required was, in many cases, changing or not yet available. As a result, any conclusions presented are of necessity, based on the information available at this time.

This report describes the basic ground rules of the study and presents the nominal LEM mission profile with emphasis on navigation, guidance and flight control and on crew participation in these operations.

The system functions required to replace these crew activities in an automatic mission are outlined and the results of detailed hardware studies on performing some of these functions are discussed.

2. GROUND RULES

The automatic LEM mission will begin with the Apollo in lunar orbit. The two man crew and associated scientific equipment will be the payload in the "automatic LEM". By definition, the "automatic LEM" crew will perform no contributory function to operation of the LEM vehicle. There is however, one exception. It has been defined that LEM IMU alignment before separation will not be required as part of the automatic mission.

It was assumed that the crew member on the CSM could be utilized to perform remote control and decision functions. It is felt strongly that human judgement is required to assess the lunar terrain and select the final landing site.

The automatic function shall be achieved by utilizing the existing LEM configuration and flight plan where reasonable and practical. The changes made will be modifications or additions to existing LEM equipment.

The main concern of the study has been and will continue to be the guidance and navigation aspect of the problem, although other aspects may be considered, if they are of sufficient importance.

At the present time, no consideration has been given to automatic abort.

[redacted]

3. NOMINAL LEM MISSION DESCRIPTION

The following description is a brief familiarization with the latest plan for the LEM mission. From this it will be seen that many of the mission phases are nominally automatic or semi-automatic in nature. However, it should be noted that there are several critical areas where manned crew inputs are required.

Pre-Separation

With the Apollo in lunar orbit (100-60 n. mi.), the LEM N & G computer is prepared for operation. The LEM IMU (inertial measuring unit) is fine aligned by the crew using the SCT (scanning telescope). Next, the radar altimeter system is activated by the crew. The desired landing site has been selected from the CSM utilizing the sextant provided.

Separation

The LEM crew initiates separation. There is a LEM translation away from the CSM along its X axis. This is manually controlled by the crew utilizing the RCS (Reaction Control System). During this translation the LEM attitude is held constant automatically using N & G (Navigation and Guidance) stabilizing signals to the RCS.

Reorientation for De-Orbit Boost

Except for initiation, this complete maneuver is automatic, controlled by N & G system command signals to the RCS jets. It consists of accurately controlled pitch rotation, and yaw axis hold. The roll axis attitude is coarsely held.

Injection Into Synchronous Transfer Orbit

This complete maneuver is automatic and controlled by N & G system command signals to the RCS and main engine. Pitch and yaw attitude control is precise. Roll control is coarse. Main engine thrust turn on and cut-off is commanded from the N & G system.

Descent Coast

The attitude rotation maneuvers for observation and preparation for powered descent are automatic and controlled by N & G system command signals to the RCS. The radar antenna control is either manual or commanded through the computer to acquire the CSM. The radar altimeter is manually activated and checked prior to powered descent. The crew surveys the landing site from the LEM. The coast period ends at 50,000 feet pericynthion. (There is a possibility that an extra orbit would extend the coast phase. In this case, the IMU would require additional fine alignment).

Powered Descent

The LEM attitude and rotation program is automatic. The RCS servo-loop gain control (which is required due to large changes of vehicle moments of inertia) is automatic with manual override. During this phase, a pre-computed precision pitch program will most likely be imposed and accurate yaw and roll control required. The navigation and guidance system command signals control the RCS for attitude and the main engine for velocity changes. The altimeter is put into operation by the LEM crew and is used for obtaining data on altitude and velocity for updating the N & G system. The crew surveys the landing site with the SCT. This powered descent phase is ended with an automatic flare starting at 5,000 to 10,000 ft. and terminated at 1,000 feet and LEM velocity is reduced to zero or near zero.

Hover, Terminal Descent and Touchdown

During flare out to hover, the LEM vehicle is manually or automatically pitched to the vertical. In hover there may be a manual roll rotation for landing site inspection. Visual landing aids (flares, landing lights, etc.) are deployed. The characteristics of the terrain are checked and an actual landing site chosen.

The descent is performed either automatically, with capability for manual override and modification of the automatic descent or completely manually. Therefore, thrust and RCS control is derived either by command from the N & G subsystem or from the crew. Translation is accomplished by rotating the vehicle until the required horizontal thrust component is attained from the descent engine. The RCS is employed for vernier translational control. The RCS servo loop gain control is automatic with manual override.

Post Landing Phase

Using either data derived from the radar or the SCT, the crew establishes the LOS to CSM. The radar tracks the CSM to establish its orbital plane. Two known stars may be sighted by the crew to establish orbital plane reference. The crew aligns the IMU with the local vertical and parallel to the CSM's orbital plane.

The crew programs the N & G computer for ascent trajectory control. The computer is activated and guidance mode selected. Overall check-out of LEM systems is performed. After this is accomplished, the vehicle is put in a power standby condition and the crew continues the mission. Power is turned on again to repeat the above sighting and alignment procedure when it is necessary to prepare for the ascent boost phase.

Ascent Boost

This phase is completely automatic except for crew checks. The N & G system commands the automatic firing of the ascent stage. The N & G system commands a precise programmed pitch rotation to establish the ascent trajectory. Precise yaw and roll control is also held. The trajectory consists of a vertical rise and a pitch over to a horizontal flight path angle at 50,000 ft. altitude. The crew previously had determined whether to establish a parking orbit or to continue through to a Hohmann transfer based upon the LEM - CSM phase angle at launch. Assuming the parking orbit is not chosen, the Hohmann transfer (ascent coast) is started.

Ascent Coast

The coast phase is a semi-automatic mode. The LEM vehicle will continue on its coast trajectory with midcourse corrections being commanded by the N & G system to the RCS. During this phase, only a coarse attitude hold about all 3- axes is required. Reorientations for observation of CSM may be performed automatically or by manual commands from the crew. In preparation for rendezvous, and midcourse corrections, the LOS to the CM is obtained by either manually slewing the SCT and rendezvous radar or by computer commands.

Rendezvous

This phase can be completely automatic once the LOS to the CSM is obtained and the radar is locked on. The N & G system will then compute terminal corrections for adaption to the CSM orbit through translational and rotational commands to the RCS. During this phase there is precise control about all three axes. The crew merely monitors LOS nulling and R and $\dot{R}$ as the LEM closes on the CSM. When range is less than 500 feet and range rate is between 0-3 ft./sec., preparation for docking begins.

Docking

This phase is performed manually. The LEM crew will command angular rotations or translations utilizing the RCS in the attitude hold mode. The crew prepares for docking by selecting the docking hatch, turning on docking lights, etc. The closing and lateral translation rates are manually reduced to approximately 1 ft./sec. Attitude rates are manually reduced to approximately 1°/sec. The maneuver is continued until final attachment to the CSM is attained.

4. REQUIREMENTS FOR A COMPLETE "AUTOMATIC" MISSION

In order to fully automatize the mission, the following automatic functions must be accomplished during each phase.

Pre-Separation

1. Automatize star sights and fine alignment of IMU.
2. Automatize N & G computer preparation and activation of radar altimeter.

Separation

1. Either have CSM crew perform the translation for separation or automatize the translation from the LEM.

Reorientation for De-Orbit Boost

1. Except for initiation, this phase in normally automatic.

Injection Into Synchronous Transfer Orbit

1. Nothing need be done as this phase is normally automatic.

Descent Coast

1. Gimbaled radar must be automatized to search for and lock onto the CSM.
2. Automatize star sights and fine alignment of IMU, if there is an extra coast orbit.
3. Automatize preliminary activation of radar altimeter.
4. CSM could remotely survey landing site (optional).

Powered Descent

1. CSM could remotely survey landing site (optional).

2. Automatize final activation of radar altimeter.

Hover, Terminal Descent and Touchdown

1. Automatize dropping of visual landing aids.

2. Automatize vehicle pitch to the vertical at hover point.

3. Automatize the descent trajectory and attitude control to touchdown.

4. Remotely monitor surveillance of landing site from CSM.

5. Automatize translational maneuver required to change landing site location.

Post Landing Phase

1. Automatize radar search and lock on to CSM.

2. Automatize star sights and IMU alignment.

3. Automatize programming of N & G computer for ascent trajectory.

4. Automatize system checkout and preparation for launch.

Ascent Boost

1. Nothing need be done, as this phase is normally automatic.

Ascent Coast

1. Automatize radar acquisition of CSM.

2. Automatize attitude commands for sighting or visual checks.

Rendezvous

1. Nothing need be done, as this phase is normally automatic.

Docking

1. Either have CSM perform docking or automatize the LEM's

docking procedure to CSM.

Summary

In summary, the following functions must be performed automatically or remotely from the CSM:

1. Star sighting and IMU alignment.
2. Remote survey of landing site from CSM.
3. Descent trajectory and attitude control from hover point to touchdown.
4. Radar acquisition of CSM.
5. Switching, programming, system activation and power shut down.
6. Docking and separation.

5. DISCUSSION OF AUTOMATIZED FUNCTIONS

Detailed consideration will now be given to each of the functions which are to be "automatized".

Docking and Separation

Separation is automatic except for the manual translation. There appears to be no real advantage to automatizing the separation translation maneuver along the X axis. It is a very simple operation and is just as easily performed by the CSM. When the CSM performs the translation, the LEM may remain passive in translation and as previously in an attitude hold control mode about all three axes.

In contrast the docking maneuver is almost entirely manual, probably requiring LEM attitude hold about all three axes, and is a fairly complex maneuver. This type of operation is delicate and it requires a great amount of flexibility to make the necessary adjustments for a successful docking.

In order to perform the final contact and coupling operation automatically, it is required that there exist a highly accurate knowledge in relative angular and translational rates between LEM and CSM. It also requires an accurate knowledge of relative angular and translational positions. As a result, feasibility of automatic docking may be severely limited by sensor accuracies.

On the other hand, the manual control method offers flexibility since the docking partner may be kept in view. As in separation, the CSM may dock to the LEM with the LEM in a passive translation and attitude hold mode.

It should also be noted that during the Apollo mission, just after earth orbit and lunar injection, there is a transposition and rotation where the CSM separates and performs a 180° rotation with respect to the LEM and then again docks to the LEM, which certainly demonstrates the ability of the CSM to perform separation and docking functions.

Therefore, from the standpoint of minimizing modification to LEM, simplicity, reliability, and flexibility it appears that the CSM should perform docking and separation rather than automatize the LEM to perform these functions.

Switching, Programming, System Activation and Power Shutdown

During the course of the nominal LEM mission, a certain amount of mannual switching is required. The N & G computer must be prepared for operation and programmed during Pre-separation and Post Landing phases. The radar altimeter must be activated and checked during the Pre-separation, Descent Coast and Powered Descent Phases. The gimbaled radar must be activated and checked during the Descent Coast and Post Landing phases. The descent and ascent engines and RCS must be pressurized and checked by pushbutton operation and meter monitoring during Pre-separtion. The descent engine is manually fired based on the timing display for Injection and again for

Powered Descent. During the Post-landing phase, the descent stage is permanently shut down by manual switching. Also, the ascent and RCS systems are pressurized and checked as previously at certain time intervals until Ascent. Ullage is normally provided by activating the RCS X-axis thrusters before main engine firing. Tank switchover is an abort mode which is normally performed manually. In addition, there are other miscellaneous switching functions required. Some of these functions may be performed remotely from the CSM if the control, switches and required display indicators are provided. The remaining functions may be programmed. For ullage, the X axis RCS thrusters may be fired prior to all main engine firings in order to eliminate remote commanding from the CSM. (The additional fuel used would be very small). The CSM-LEM communications link could probably be utilized for the remote operation since bit rate requirements for this type of On-Off command is generally small. This area does not seem to present a problem in the LEM from a weight and implementation standpoint, although additional switching and display equipment must be added to the CSM. Further studies are required to pinpoint switching operations and switching frequency in order to exactly specify the equipment changes required.

Radar Acquisition of CSM

Radar acquisition of the CSM from the LEM is required during the Descent Coast, Post Landing, Ascent Coast and Rendezvous phases.

The LEM digital computer can compute the CSM position during descent as a function of time based on its position before separation. During lunar surface stay time the computer power is shut down, but a clock could keep track of time, so that when the computer is reactivated the CSM position may be updated. Upon command from the CSM crewman, the LEM digital computer may command an initial angular position for the LEM gimbaled radar antenna, which should be near enough to the actual CSM position to enable acquisition (see discussion on star sighting and IMU alignment). The radar at this time will be in an automatic track mode and can first search for and then lock on to the CSM.

Although the primary navigation and guidance system including computer and the radar have not been completely defined, it is understood that the computer and radar will contain the required capability to perform the above mentioned functions.

6. REMOTE SURVEY OF LANDING SITE

Introduction

In Section 4 it has been stated that remote surveillance of the landing site during hover and terminal descent is desirable. Remote monitoring may be instrumented by placing a television camera in the LEM and a television display in the CSM such that the landing point is in view during the critical portion of the descent. This would present the required data to the CSM crewman to enable him to make a decision regarding a change in the target landing site coordinates. During this phase of the mission, it is planned to have an automatic pre-programmed descent trajectory capable of being modified by manual inputs. If the landing site is changed, a new automatic trajectory is computed to guide the LEM to the newly selected landing point. This would remove the burden of remote, manual piloting to touchdown based on a display that may perhaps not be as suitable as an actual view of the site.

Some of the areas which will be considered in the following discussion on remote display of the landing site are: Light available for TV camera, lens and angle required based on light and resolution required, use of artifical light to supplement natural illumination, placement of TV camera, TV camera bandwidth and display flicker rate.

Light Available and TV Camera

In the lunar day, the light available by reflection from the moon's surface will be more than sufficient for effective remote surveillance. However, in earthshine the illumination level becomes marginal with respect to TV camera sensitivity. To implement the remote surveillance feature, there is a choice of two TV camera types. One is the Vidicon, weighing approximately 5 pounds, the other is an Image Orthicon, weighing approximately 40 pounds. From the standpoint of weight, reliability, complexity and wattage required, the Vidicon is to be preferred. From the standpoint of ability to operate on marginal light, the Orthicon is superior, since it requires 1/10 the illumination of the Vidicon camera.

There is approximately 0.1 ft-candles of light reflected from the moon's surface during earthsine. This is at the marginal point for operation of the Vidicon camera.

Lens Required

The lens required will be specified by two important factors, the f number and the field of view or lens angle. (It is assumed that the resolution is limited not by the lens quality but the TV display and TV camera). The first factor is based on the light which must be gathered and transmitted to the Vidicon camera pick-up tube and the second factor is based on resolution of the TV picture.

With the earthlight available and assuming a lens transmission factor of .8, a Vidicon tube requiring .1 ft-candles, it has been determined that the f number required is approximately f/.5. Further investigation must be performed to determine practicality of the lens. It is known that the lowest f number lenses in use are f/.7. Whether this is a lower limit is yet to be determined. The formula used for this calculation is as follows:

amount of light required at photocell

$$= \frac{\text{surface incident light} \times \text{reflection factor} \times \text{optical transmission factor}}{4\ f^2}$$

The angle requirements for the lens field of view is determined by the TV display resolution requirements. The following discussion applies to a straight vertical descent trajectory. It is assumed that at a 1000 ft. range from the landing site, a 2.5 ft. object should be distinguishable on the TV display at the CSM. In addition, a one foot object should be distinguishable at approximately 400 ft. until touchdown. If the field of view is selected at 50° to satisfy the 2.5 ft. resolution requirement, then 1 foot resolution is achieved at 360 ft. However, as will be discussed subsequently, a 70° field of view would be required as the landing site is approached. This will provide view to enable last minute changes in the target landing point. The factors assumed for the TV display are: aspect ratio 4/3, number of effective lines 500, and objects must be displayed on a minimum of two lines to be distinguisable.

Appendix A indicates the method of resolution calculation and derivation of formula required for the simpler case of a vertical camera angle. Knowing the size of the object to be distinguished, and the distance of the camera from the target site, field of view may be directly calculated, or vice versa. The formula given applies only to the case of a 500 line TV display, but may be easily modified for any number of lines.

TV Camera Bandwidth

The bandwidth required is essentially a function of the number of lines (or resolution) and the frame rate of the display, since these parameters determine the information rate transmitted over the communication link. The relationship between these parameters is given by the following expression:

$$f = \frac{1}{2} \; a \, (N_L)^2 \, K \, fv$$

where a = aspect ratio = 4/3 for optimum view

N_L = total number of horizontal lines = 500

f_V = frame rate = 30 cps (with 2 to 1 interlaced scanning)

K = constant typical value = .8

f = video band width in cps

$$f = \frac{1}{2} \frac{(4)}{(3)} \; (500)^2 \; (.8) \; (30) = 4 \times 10^6 \text{ cps} = 4 \text{ mc}$$

This bandwidth may be reduced if the frame rate is reduced to 10 frames/sec. in which case the required bandwidth would be 1.33 mc.

Further study is required to see what the lower limit on frame rate is to display an acceptable picture.

The present communication link between the LEM and CSM is not usable for the TV transmission bandwidths required. This would mean that either an additional link would be required for TV alone or that a link of greater capacity would have to replace the original one.

Use of Artificial Light to Supplement Earthshine

Assuming a 50° lens field, an incandescent lamp could be focused within the same 50° cone. A 1000 watt type H A-H6 #744 incandescent bulb gives a total of 65,000 lumens. At 1000 ft. vertical altitude the area covered by a 50° cone is 680,000 square feet. Thus, the light illuminance incident on the moon's surface would be approximately 0.1 lumens/ft.^{2} or .1 ft.-candles. This is approximately 1/14th of the light which would be received by the moon from earthlight. Therefore, to match earthlight 14,000 watts would be required. This amount of power is not practical at the present time, and it appears that some other means will have to be found to supply artifical light. Flares may be more suitable for the high lighting and short period of time involved. Further study should be made for determining the feasibility of flares.

It is also possible that the Vidicon camera may be improved in sensitivity to the point where light requirements are no longer marginal.

Placement of TV Camera on the LEM

There are many possible terminal descent trajectories from the 1000 ft. hover altitude which are feasible for the automatic LEM. A study has been initiated to propose and determine the optimum one. Figure I presents one trajectory profile which is under consideration and may perhaps be representative. This figure is a plot of LEM altitude as a function of downrange location, with vehicle pitch attitude identified at various points along the curve. (Attitude angle is measured from the right hand side of the horizontal in a counterclockwise direction). The pitch angle early in the descent of 68.5° reflects the necessary angle of the thrust vector to impart a horizontal motion from the zero velocity hover condition at 1000 ft. This maneuver introduces high pitch rates and offers poor visibility at start of descent. This problem may be alleviated by allowing a small residual horizontal velocity component (100 ft. sec.) at hover instead of reducing all components to zero. If all velocity components must be reduced to zero then a gain change in the guidance law mechanization may reduce the severity of the pitch maneuvers. This problem is to be studied further and this trajectory is only presented here to serve as a framework to study the camera placement problem.

It is desireable to place the camera in a fixed position to avoid the weight and complexity of stabilizing a gimbaled mount. Therefore, some investigation was made into the mounting of a camera in a fixed location.

Figure 2 is the visual down range coverage obtained with a fixed camera axis placement at an angle of 45° from the thrust axis using the trajectory in Fig. 1. The lens field of view is 50°. In order to obtain the visual coverage down range, enter the shaded curve at the known LEM altitude and read off the upper and lower point of the shaded area. The relative position of the landing site in the visual field of view is also indicated. If down range location is known, enter the curve on the vertical axis intersecting the dotted line (labeled Down Range Position of LEM). Projecting vertically gives the same information as above and, in addition altitude of LEM. Inspection of this figure indicates that the landing site is out of view for the last 70 feet of altitude descent. This may be rectified by employing a wider field lens at this point or sooner as long as the resolution requirements are not exceeded (see section on Lenses for method of computation). Figure 3 shows the affect of using a 70° lens from the onset at the 1000 ft. hover point. In this case, the landing site is seen for essentially the whole trip. A disadvantage of this is that no area beyond the landing point is seen for the last 10 feet. In addition, the resolution requirements utilizing a 500 line TV display are not met. A means to increase the area beyond the landing site is to shift the camera lens angle forward, at the appropriate point, and the means to satisfy the lens resolution requirement is to switch lenses at the appropriate point. This implies use of a turret lens and a movable prism lens system both driven by remote command.

Figure 4 indicates the results of employing the above as a typical means of satisfying resolution and visual requirements. Initially, a 50° lens is placed at an angle of 45° with respect to the thrust axis.

At approximately a 150 foot altitude, switch over is made to a 70° lens with a turret lens arrangement to enlarge the field of view. At a 50 ft. altitude the mount is then switched to a second preset position (forward 5°) making a 50° angle relative to the thrust axis.

7. STAR SIGHTING AND IMU ALIGNMENT

The alignments and sightings required during the mission are summarized as follows:

1. Fine align IMU by tracking two stars during pre-separation.
2. Fine align IMU by tracking two stars during the descent coast phase, if an extra orbit is incorporated in the mission profile.
3. On the lunar surface, track two known stars and align IMU to CSM's orbital plane and local vertical. Then power is removed from N & G. Power is restored in preparation for ascent.

In case 1 above, provision for automatic alignment is not required since it has been directed that this need not be considered prior to separation. For cases 2 and 3 two procedures are discussed. One is based on the assumption that the LEM vehicle does not change attitude after landing. The other would be utilized if there is a change in attitude after landing which is not measured by the IMU due to power shut-off. Both methods require use of an automatic star tracker, computer stored star table and additional computer programming.

The first procedure would operate as follows:

Upon remote command from the CSM, the automatic star tracker would be commanded by the digital computer to sequentially point at two stars and track them. The data for positioning the star tracker would be available if the following contraints are observed:

Before Touchdown

a. The IMU is lined up with the original inertial reference (with some small error due to normal equipment drifts, sensor accuracies and biases).

b. The computer has stored the table for star location with respect to this same reference.

c. The attitude of LEM vehicle with respect to the IMU can be derived from gimbal pick-offs.

After Touchdown

d. With the N & G system still operating, the attitude of the platform continues to remain constant with respect to inertial space. The attitude of the vehicle, however, starts to change with respect to the IMU due to the Moon's rotation and the moon-earth motion. The instantaneous attitude is read from gimbal pick-offs relative to LEM. Therefore, the star tracker may still be computer positioned based on star tables, time, LEM location on Moon's surface, and a knowledge of LEM star tracker unobstructed view.

When power is shut down, the following parameters may remain stored in the computer memory:

a. Latitude and longitude of LEM on Moon's surface

b. Last yaw, roll and pitch attitude with respect to the original inertial reference.

c. Last CM orbit.

It is assumed that the clock continues to run.

Based on the above assumptions, it is possible to compute the new LEM attitude with respect to the old reference. The old reference may be first set up by commanding to the IMU the stored yaw, roll and pitch angles relative to LEM prior to shutoff. Since the LEM change in attitude may be computed based on time and the known motions of the Moon, this may be added to the old attitude angles to re-derive the original inertial reference. To obtain the present orbit of the CM relative to the LEM for radar or IMU positioning, the stored orbit must be modified according to the computed change due to Moon's motion.

If it could not be assumed that the LEM attitude change at landing is insignificant,then another procedure must be followed. In this case, star sightings must be taken to establish the azimuth orientation of the table (the local vertical could be sensed by the accelerometers). If the azimuth reference is lost, then the automatic star tracker would have to search the whole 360° field in azimuth. There are two methods to obtain a more direct pointing. The first method is to utilize a pattern recognition device which crudely identifies groups of stars. Some preliminary work has been done in the development of such a device. The second method is based on the fact that no pair of stored stars below some magnitude have equal angular separations (minimum difference 1/2°). The star tracker would start searching at its random azimuth position and would lock on to the first star of sufficient brightness it encounters. The next step would be for the computer to start down the star table at the various angular separations and position the star tracker accordingly until it locks onto the next star. When this happens the location and identity of both stars are known because the angle is unique. Next, azimuth direction may be obtained from a star table and the IMU may be aligned. The equation to calculate the angle between two stars for comparison with the angles is as follows:

$$\cos \gamma = \sin E_a \sin E_b + \cos E_a \cos E_b \cos (\psi_a - \psi_b)$$

γ = angle between two stars sighted

E = declination of stars in celestial coordinates

ψ = azimuth of stars in celestial coordinates

a, b = subscripts for two stars a and b

Further study would be required to determine the search time and program changes required based on derived equations simulating the live situation.

8. SUMMARY AND RECOMMENDATIONS

In the preceeding discussion, it has been seen that the following functions must be automatized or performed remotely to satisfy the requirements of a completely automatic mission:

Star sighting and IMU alignment.

Survey of landing site from CSM.

Descent trajectory and attitude control from hover point to touchdown.

Initiation of ullage thrust.

Radar acquisition of CSM.

Switching, programming, system activation and shutdown.

Docking and separation.

The most critical problem areas are the automatic IMU alignment and the requirement for remote survellance of the landing site. Automatic alignment requires added weight and complexity since automatic star trackers must be employed. The remote survey of landing site is critical because, in addition to added equipment, it imposes bandwidth requirements which exceed that available in the present LEM-CSM data link design.

The following discussion will summarize the conclusions and recommendations of the automation study:

Star sightings for IMU alignment require the addition of an automatic star tracker and possibly of a star pattern recognition device. TAKE OFF

Remote survey of the landing site from the CSM utilizing TV is practical with the addition of TV camera on the LEM, display on CSM and replacement of the data communications link between LEM and CSM with one of much wider bandwidth. Further investigation is required for determination of minimum bandwidth requirements. Provision of artifical illumination for the recommended Vidicon camera by means of flares rather than incandescent light should also be studied. (Cursory investigations indicate that flares have a very favorable light per unit weight ratio and sufficient peak light outputs for short time durations). A fixed TV camera mounting with a turret lens and a two position lens arrangement will provide satisfactory capability for remote landing site surveillance, as indicated by a visibility study of a typical descent trajectory. LANDING

Automatic radar acquisition of the CSM appears to be a capability already essentially designed into the system. TAKE OFF

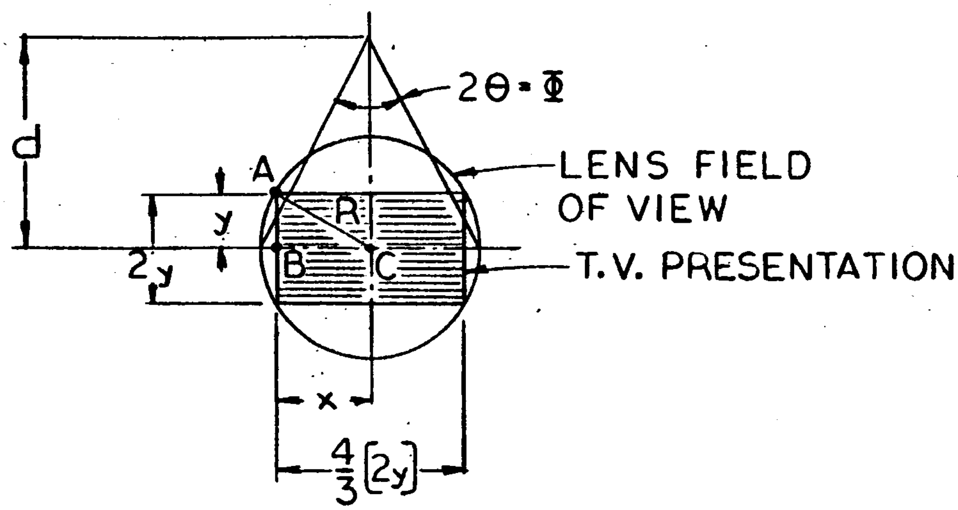
It is recommended that docking and separation maneuvers be performed manually be the CSM crew members rather than automatically by the LEM. EXISTING

Switching, activation, programming and monitoring functions may be performed either remotely by installation of the necessary controls and displays in the CSM or by LEM programmed operation. Further mission and equipment study is required to determine the optimum implementation of each function.

Study has begun to investigate various guidance laws and trajectories which could be suitable for an automatic descent to touchdown.

An estimate of additional weight and power required to perform the LEM mission automatically has not been derived since the redirection of the study has eliminated the need for remote IMU alignment and landing site surveillance, which would create the greatest hardware weight penalty. The next report presenting the results of studies performed under the new ground rules, will indicate the detailed hardware implications.

APPENDIX A



Definition of Symbols:

Φ = 2θ = lens field or lens angle

d = distance from TV camera on LEM to landing site (ft)

2y = short side of viewed rectangle (ft)

q = ft/line of TV required

S = minimum size in ft. of object to be distinguished

Derivation of Formula Relating Lens Angle to Object Resolution

$$\tan \theta = \frac{R}{d}$$

Since ABC is a 3:4:5 right triangle, the following relations hold:

$$\frac{4}{5} R = x = \frac{4}{3} y$$

since $R = \frac{5}{3} y$

$$\tan \theta = \frac{5}{3} \frac{y}{d}$$

$$2y = 500 \text{ lines x } q \text{ ft/line}$$

$$y = 250 \; q \text{ ft.}$$

$$\tan \theta = \frac{5}{3} \frac{250q}{d}$$

$$\tan \theta = 417 \frac{q}{d}$$

If 2 lines are required to resolve an object - and S is the size of the object to be resolved, specification of size of object to be resolved S is related to q as follows:

$$q \text{ ft/line} = \frac{(s \text{ ft})}{2 \text{ lines}}$$

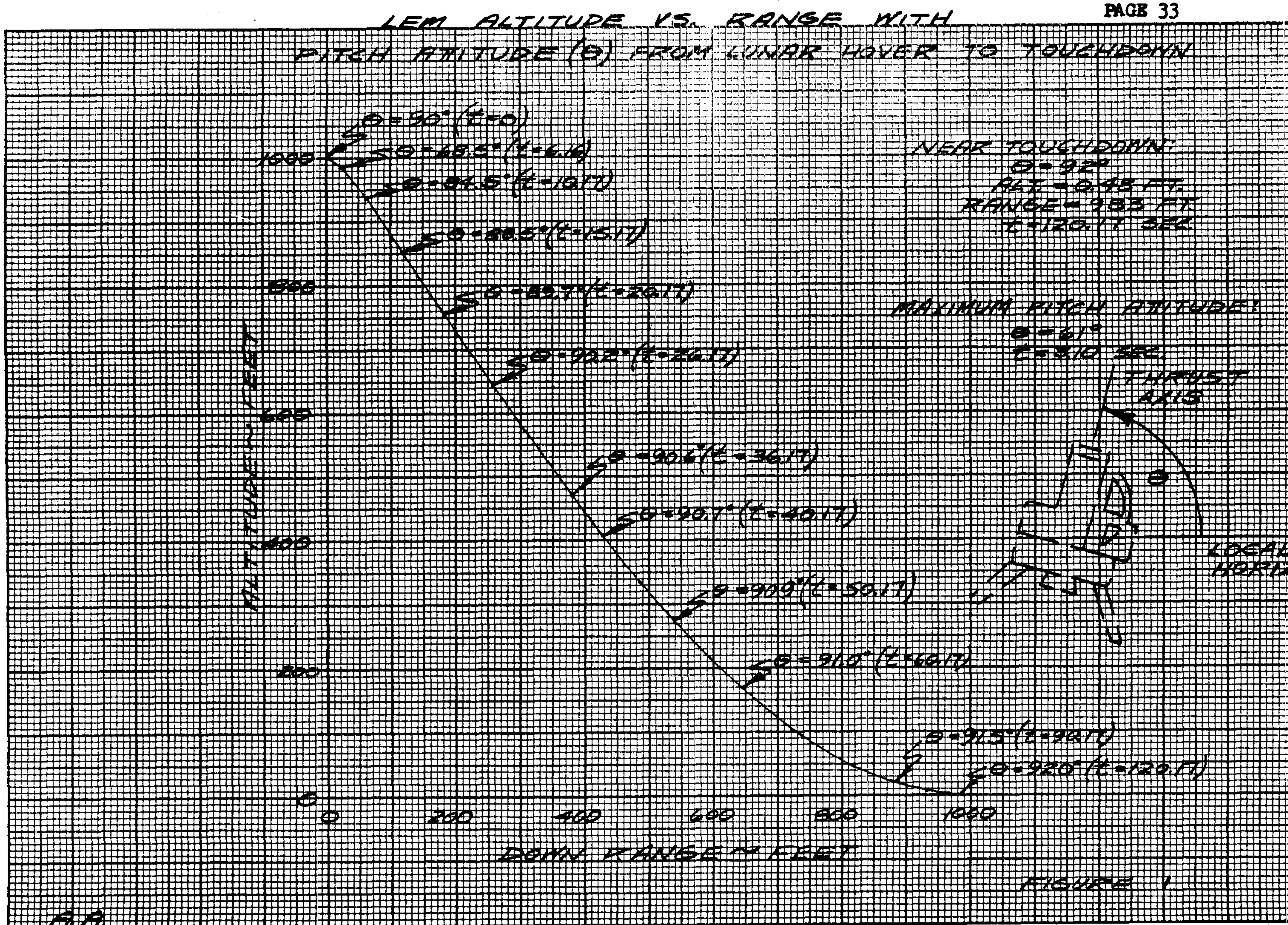
$$q = \frac{s}{2}$$

$$\tan \theta = 417 \frac{(s)}{(2d)} = 208.5 \frac{s}{d} \simeq 209 \frac{s}{d}$$

$$\tan \theta = 209 \frac{s}{d}$$

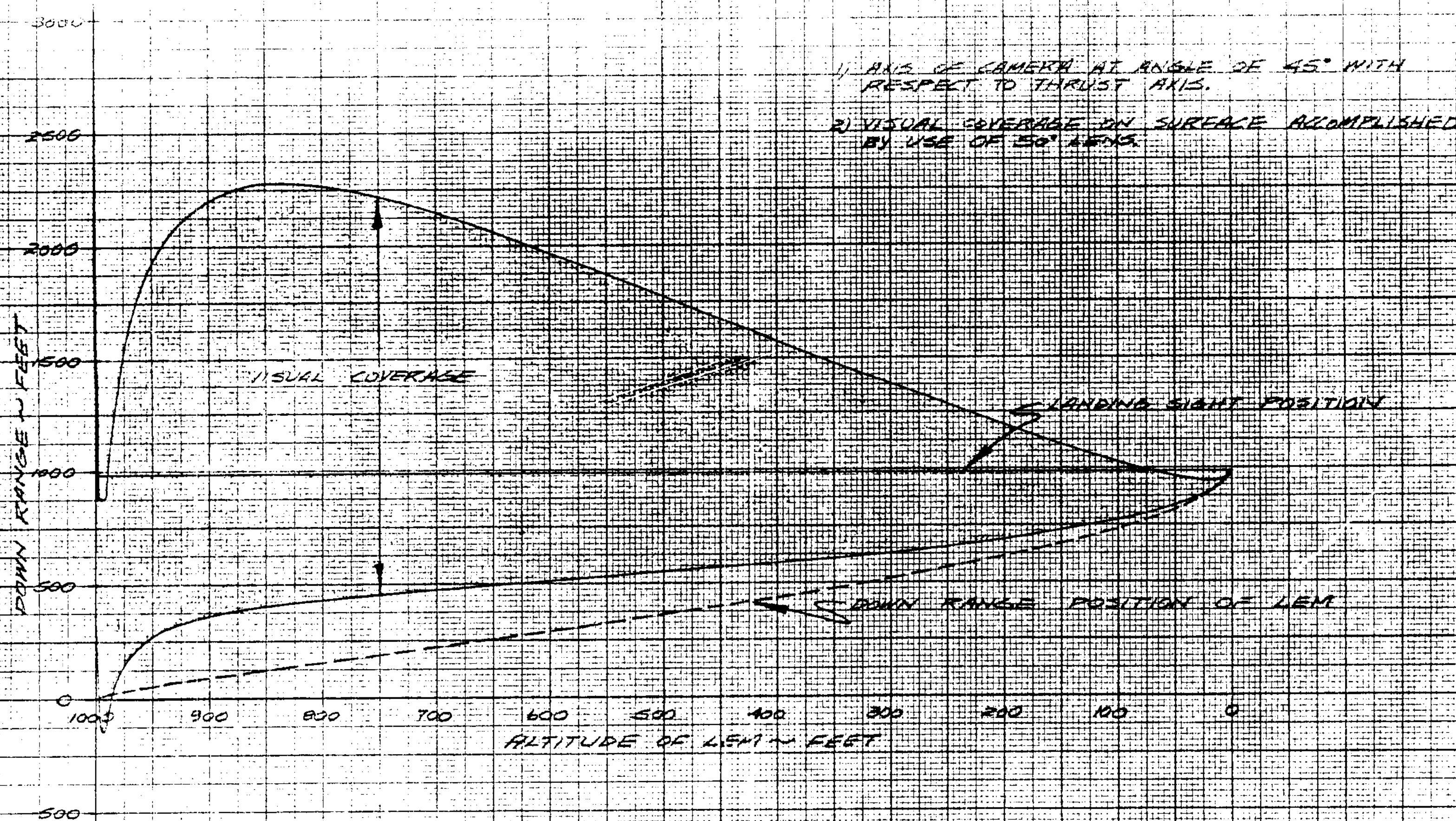
$$\Phi = 2\,\theta = 2\left[\tan^{-1} \frac{209s}{d}\right]$$

$$\Phi = 2\left[\tan^{-1} \frac{209s}{d}\right]$$


LEM ALTITUDE VS. RANGE WITH
PITCH ATTITUDE (θ) FROM LUNAR HOVER TO TOUCHDOWN
θ = 90° (t = 0)
θ = 84.5° (t = 10.17)
θ = 92.2° (t = 26.17)
θ = 90.6° (t = 36.17)
θ = 90.7° (t = 40.17)
θ = 90.9° (t = 50.17)
θ = 91.0° (t = 60.17)
θ = 91.5° (t = 90.17)
θ = 92.0° (t = 120.17)
NEAR TOUCHDOWN:
θ = 92°
ALT = 0.45 FT.
RANGE = 983 FT
t = 120.17 SEC
MAXIMUM PITCH ATTITUDE:
θ = 61°
t = 3.10 SEC
THRUST AXIS
θ
LOCAL HORIZ.
ALTITUDE ~ FEET
1000
800
600
400
200
0
0
200
400
600
800
1000
DOWN RANGE ~ FEET
FIGURE 1

[redacted]

LEM VISUAL DOWN RANGE COVERAGE AS A FUNCTION OF ALTITUDE OR LEM RANGE (50° CAMERA LENS)



F. G.

FIGURE 2

[redacted]

[redacted]

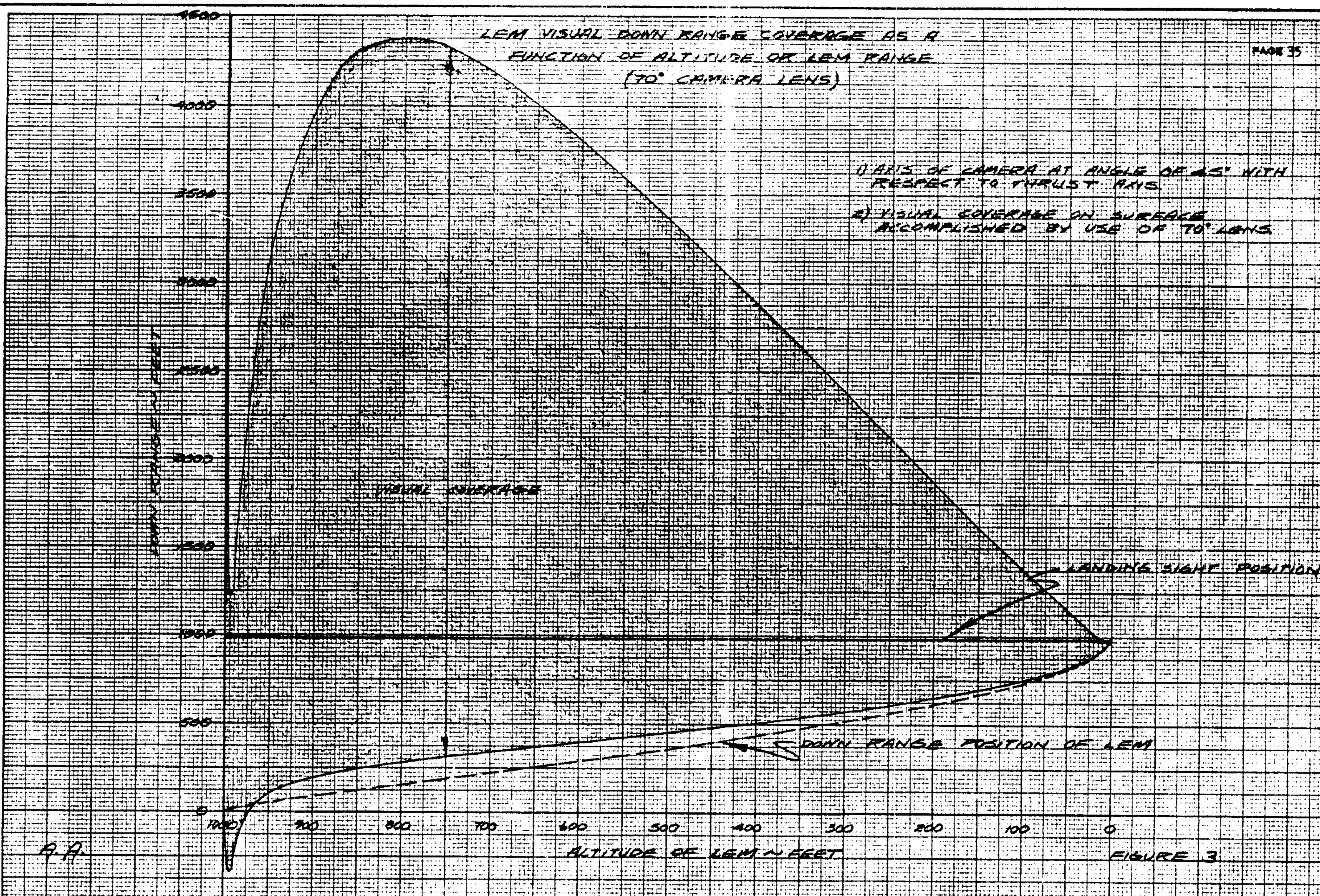


FIGURE 3

Contract No. NAS 9-1100
Primary No. 013

[redacted]

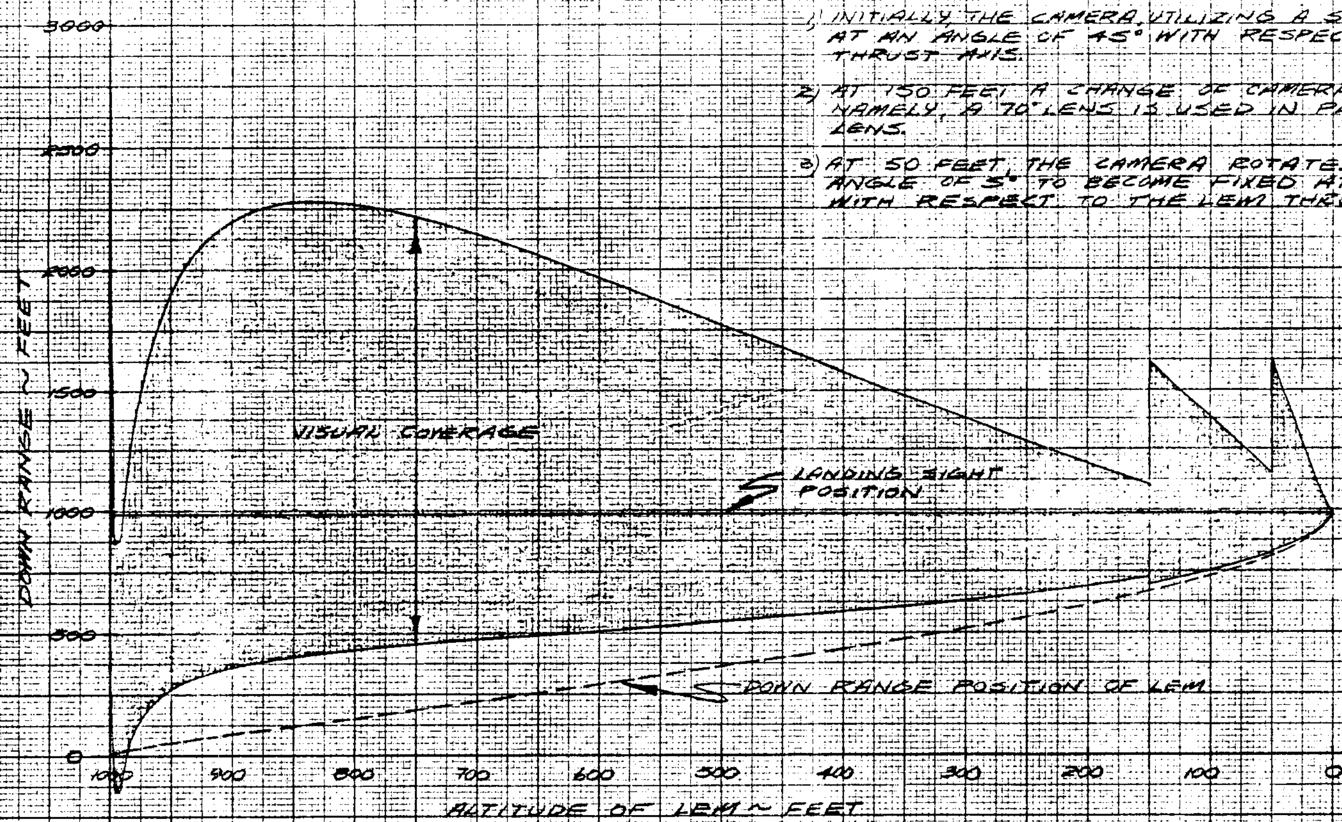
[redacted]

LEM VISUAL DOWN RANGE COVERAGE AS A FUNCTION OF ALTITUDE OR LEM RANGE
(COMBINING 50° AND 70° LENSES AND ONE CAMERA REPOSITIONING)

1) INITIALLY THE CAMERA, UTILIZING A 50° LENS, IS FIXED AT AN ANGLE OF 45° WITH RESPECT TO THE LEM THRUST AXIS.

2) AT 150 FEET A CHANGE OF CAMERA LENSES OCCURS; NAMELY, A 70° LENS IS USED IN PLACE OF THE 50° LENS.

3) AT 50 FEET, THE CAMERA ROTATES THROUGH AN ANGLE OF 5° TO BECOME FIXED AT AN ANGLE OF 50° WITH RESPECT TO THE LEM THRUST AXIS.



F. A.

FIGURE 4

[redacted]